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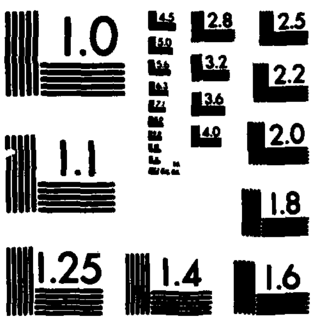

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TECHNICAL REPORT

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CALCULATION OF VELOCITY PROFILES AND VISCOUS HEATING EFFECTS IN PROPELLANT EXTRUSION DIES

R.C. WARREN

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R.C. Warren

S U M M A R Y

The flow of a propellant dough in capillary and annular dies has been analysed with a finite difference computer program. Velocity profiles have been calculated and the effects of viscous heating at the high extrusion rates used in propellant processing have been investigated. Viscous heating was found to have a dramatic effect, causing considerable rearrangement of velocities in the die. It is suggested that viscous heating reduces extrusion pressures and die swell and it may have a beneficial effect on extrudate surface finish.

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1. INTRODUCTION

Gun propellants can be manufactured by a range of processes, most of which involve extrusion through dies to produce the required cross-sectional shapes. Irregularities in dimensions of propellant grains caused by poor extrusion can result in unacceptable variations in muzzle velocity and gun pressure. Some of the problems encountered in extrusion are die swell, surface roughness and melt fracture.

Little is known either about the way propellant doughs flow in dies, or about the rheological properties of propellant doughs. However, they must have a strong influence on extrusion behaviour. An analysis of the factors affecting propellant extrusion is necessary, but the task presents considerable difficulties. The geometries of dies are often complicated and no satisfactory constitutive equations describing polymer flow are yet available. A further complicating factor is that extrusion often takes place at rates where viscous heat generation can be expected to occur. In the extrusion of polymers, viscous heating is known to cause large radial temperature gradients and velocity rearrangements(ref.1). A comprehensive review of viscous heating has been given by Winter(ref.2). Quantitative analysis of heating effects in dies is difficult, as viscous heating is described by coupled, non-linear differential equations which require numerical methods for solution.

In this report, a finite difference program has been used to calculate velocity profiles in the shape forming sections of three propellant extrusion dies. The dies analysed were a solid cord die for casting powder, a single pin die for small arms propellant, and a 7 pin die for cannon propellant. The effect of viscous heating in the solid cord and single pin dies was calculated. Various approximations were made, but the results illustrate the kinds of flow which may be encountered in extrusion, and the importance of viscous heating.

2. PROGRAM

The mathematical model used in this work has been described by Cox and Macosko(ref.1) and the basic computer program was obtained from the Ph.D thesis of Cox(ref.3). The model includes the following assumptions.

(1) The flow is laminar and steady.

(2) The flow is axisymmetric.

(3) There is no fluid slip at the wall.

(4) All normal stresses are zero.

(5) Thermal conductivity, k, heat capacity, Cp, and density, ρ, are independent of temperature and pressure.

(6) Viscosity, η, can be expressed as a function of shear rate, $\dot{\gamma}$, and temperature, T.

With these assumptions the equations describing flow in a capillary reduce to :

$$\frac{\partial V_z}{\partial z} + \frac{1}{r}\frac{\partial (r.V_r)}{\partial r} = 0 \qquad (1)$$

$$\frac{dP}{dz} + \frac{1}{r}\frac{\partial(r.\tau rz)}{\partial r} = 0 \qquad (2)$$

$$\rho Cp\left[\frac{Vr\partial T}{\partial r} + \frac{Vz\partial T}{\partial z}\right] = \frac{-\tau rz\partial Vz}{\partial r} + \frac{k\partial}{r\partial z}\frac{(r\partial T)}{\partial r} \qquad (3)$$

with boundary conditions:-

$\frac{\partial T}{\partial r} = \tau rz = 0$	$r = 0$	$0 < z < L$
$Vz = Vr = 0$	$r = R$	$0 < z < 0$
$T = To$	$z = 0$	$0 < r < R$
$Vz = Vz_0$	$v = 0$	$0 < r < R$
$Vr = 0$	$z = 0$	$0 < r < R$
$P = 0$	$z = 0$	$0 < r < R$
$\frac{\partial T}{\partial r} = \frac{-Nu}{R}(To-T)$	$r = R$	$0 < z < L$

R and L are the radius and length of the capillary, To the initial dough temperature, Vz(r) the inlet velocity profile assuming isothermal conditions at the inlet, Nu the Nusselt number (2hR/k), and h the heat transfer coefficient at the wall. A complete Notation of symbols is given on page 7. Cox and Macosko found that the empirical relationship

$$Nu = 1.75(wCp/kL)^{1/3} = 1.75(Gz)^{1/3} \qquad (4)$$

could be used to specify the thermal boundary condition at the wall. Gz is the Graetz number (wCp/kL) and w the mass flow rate(ref.1). This relationship leads to the following expression for heat transfer to the walls,

$$h = 0.875\frac{k}{R}(wCp/kL)^{1/3} \qquad (5)$$

which allows the temperature of the walls to increase as the dough temperature increases.

Equations (1) and (2) are integrated directly by numerical methods, and Equation (3) solved by an iterative procedure after converting it to a finite difference equation. The differences are generated on a variable spacing grid which is finest where rates of change of the variables are highest. An

initial temperature distribution is assumed and the velocities and pressures calculated from equations (1) and (2). Equation (3) is then used to calculate a new temperature distribution which serves as the basis for a further iteration. The process is continued until satisfactory convergence is obtained.

Cox's original program was written for capillary flow and it had to be extensively modified to enable it to be used for annular flow geometries. In capillary flow the integration of equation (2) is straightforward. In annular flow the integration has to be split into two parts, one part over the radius between the inner wall and the radial distance of the maximum velocity, R(Vmax), and the other between R(Vmax) and the outer wall. R(Vmax) is not known a priori and must be calculated by an iterative procedure for each axial section.

3. DIE GEOMETRIES

The flow path of dough in propellant production dies is quite complicated. Screens and sieves are used to collect any lumps or ungelatinised NC particles. The dough then flows into a distribution region in the die block containing several channels leading to as many as 64 separate dies. The dies usually taper into a final parallel section which determines the shape of the extrudate. Dies for perforated propellant grains have pins which require complicated structures to support them and these cause even more complex flow patterns.

The flow in nonparallel sections of a die is intricate and cannot be readilly modelled with the Cox program. However, insight into flow behaviour and extrusion problems can be gained by studying the flow in the die parallel sections. In this work the flow at the entrance of the die parallel section was assumed to be isothermal. As the dough progressed through the die, the velocity and temperature profiles were allowed to change in response to viscous heating.

The shapes and dimensions of the dies studied are illustrated in figure 1. The flow in the parallel sections of dies used to make solid cord casting powder for CDB propellants and in dies with single pins used to make perforated small arms propellant grains can be readily modelled. However, in multi-pin dies, such as those used for multiperforated cannon propellant, the flow is not axisymmetric and there are radial and circumferential flows caused by the outer circle of pins. To obtain a picture of the flow in this type of die, flows in two longitudinal sections of the die were studied. One section contained a diameter intersecting two outer pins, section A-A in figure 1c, and the other contained a diameter equidistant from the outer pins, section B-B in figure 1c. By symmetry, the flows in these two sections are axial and can be modelled by considering them to be sections of an axisymmetric die.

4. RHEOLOGICAL DATA

Measurements of the rheological properties of double base doughs of similar composition to casting powder doughs have been made previously(ref.4). Shear stress, surface temperature rise and die swell were measured at shear rates at the die wall ranging from from 1 s^{-1} to 1200 s^{-1}. The Cox program was tested by using the shear stress data to predict the expected surface temperature rise in capillary dies of various lengths. Good agreement was obtained between the predicted and experimentally observed values, as is illustrated in figure 2.

The rheological data for the double base dough was suitable for modelling flow

in the casting powder die. However, comparable rheological data for single and triple base doughs for modelling flows in small arms and cannon powder dies has not yet been determined. In order to illustrate the type of flow which occurs in these dies, the data for the double base dough were used.

5. RESULTS

5.1 Casting powder die

Calculated velocity profiles at the die inlet and exit, and the temperature profile at the exit, are shown in figure 3. The dough inlet temperature was 20°C. Calculations were made for an extrudate velocity of 2.5 m/s, the maximum value used in factory production. The effect of viscous heating on the exit profile is dramatic. The flow is plug-like, with virtually a constant velocity for 95% of the radius of the die. Almost all of the change of velocity occurs in the outer 5% of the radius near the die wall. The temperature rise is largely confined to the outer 10% of the radius, and reaches 50°C at the wall. The flow rate is so high there is insufficient time for significant heat conduction to the interior of the dough.

5.2 Small arms propellant die

A flow rate corresponding to a typical production extrudate velocity of 0.8 m/s was assumed. The velocity profiles at the inlet and exit, and the temperature profile at the exit, are shown in figure 4 for a dough inlet temperature of 20°C. The shear rate is given by the slope of the velocity profile and it can be seen that the shear rate is much greater at the pin than at the outer wall at both the die inlet and exit. The effect of viscous heating is to reduce the shear rate at the centre of flow and to increase the shear rate at the walls, particularly at the pin. The temperature rises are substantial, 46°C at the pin, and 30°C at the outer wall.

5.3 Cannon powder die

The flow rates used for the commercial extrusion of cannon propellant are considerably lower than those used for small arms propellants and for casting powder. Consequently the effect of viscous heating can be ignored. A flow rate corresponding to an extrudated velocity of 0.025 m/s was used in the analysis.

The velocity profiles, assuming an inlet temperature of 20°C in the two sections of the die shown in figure 1, are illustrated in figure 5. The shear rate is low near the outer wall, but near the pins it is considerably higher. The velocity profiles near the inner and outer surfaces of the outer ring of pins are different which indicates that flow near the outer pins is not symmetric. This would tend to cause the outer holes in the extrudate to be non-circluar.

6. DISCUSSION

Although the calculated velocity and temperature profiles can only illustrate the patterns of flow expected to occur in typical propellant dies, some conclusions can be drawn.

Viscous heating has a very strong effect on propellant flow. The increase in temperature causes a reduction in extrusion stresses, which in turn reduces the pressure required to extrude at a given rate. This is illustrated in

figure 2, taken from reference 4, which shows observed and calculated shear stresses vs shear rate for a double base dough extruded through a capillary die.

The low viscosity of the surface layers of extrudates due to viscous heating should contribute to an improvement in the surface finish of propellant grains. Surface finish of polymer extrudates is often marred by 'sharkskin', fine regular fissures in the surface which occur when the extrusion rate exceeds a critical value. Cogswell has shown that sharkskin is due to stretching of the surface layer of the extrudate as it leaves the die(ref.5). At the lip of the die the velocity of the surface of the extrudate goes from near zero to a relatively high value in a small distance. This acceleration of flow causes large extensional stresses in the outer layers of the extrudate. When the extensional stresses exceed the strength of the material fracture of the surface occurs. However, if the surface layer has a low viscosity the extensional stresses will be reduced and the likelihood of sharkskin occuring is consequently minimised.

The variation of die swell with shear rate for the double base dough extruded though a capillary die is illustrated in figure 6(ref.4). For each die , the swell increases with rate at low shear rates, but it peaks and then decreases at high shear rates. Longer dies show a greater decrease in swell at high rates. The shear rates at which die swell peaks correspond to the rates at which viscous heating becomes important. This suggests that the effect of viscous heating is to reduce die swell.

There are two possible ways that viscous heating can affect die swell. Firstly by changing the viscosity gradient across the die, and secondly by changing the relaxation times of the elastic stresses.

Phuoc and Tanner used a finite element program to calculate die swell for a Newtonian fluid with a temperature dependent viscosity flowing in a die with constant wall temperature(ref.6). Under these circumstances the centre of the fluid becomes hotter than the walls and there is an increasing viscosity gradient from the centre to the walls. Their calculations showed that die swell would increase with increasing shear rate as a consequence of the viscosity gradient across the die. For the cases considered in this study, the temperature gradient is opposite to that of Phuoc and Tanner, that is, the viscosity of the outer layer is less than in the interior. Under these circumstances the effect of viscous heating would be to reduce die swell.

Die swell has been related to the relaxation of elastic stresses induced in the extrudate by shear flow in the die(ref.7). Viscous heating tends to cause plug flow where most of the extrudate travels as an almost rigid body which would not give rise to die swell. Large shear stresses are confined to the small volume of low viscosity material near the wall. They should be able to relax quickly because of the high temperature and so reduce the amount of die swell.

The fact that temperature rises are confined to areas near the die walls and pins indicates that the surface of the extrudate may have properties different from the bulk material. The very high shear rates at the surface would tend to cause molecular orientation at the surface which would be frozen in as the extrudate cooled. It is also likely that the degree of gelatinisation of a propellant is affected by extrusion temperature, which should result in the surface of the extrudate being more highly gelatinised than the interior.

Sections of solid cord extruded at 300 s^{-1} when viewed under a microscope with crossed polaroids show a bright layer at the surface, see figure 7. This supports the assumption that molecular orientation occurs at the surface during extrusion of propellant doughs.

The oriented layer at the surface of the propellant grains could be expected to affect the diffusion of deterrents, and also impact fracture toughness. Further research is necessary to ascertain whether or not these effects are significant.

The largest source of error in the calculations in this report is the assumption of the rheological properties of the dough. It is necessary to determine the viscosity of the propellants doughs of interest under the conditions which occur in production for accurate calculations to be made. However, the results obtained suggest that it may be possible to design dies and to vary the rheological properties of the dough so that viscous heating could be used to improve propellant quality by reducing die swell and surface roughness.

7. CONCLUSIONS

Velocity and temperature profiles of propellant flow in three typical propellant production dies have been calculated. It has been found that viscous heating causes large temperature rises at the walls of the die and near pins and that these rises have a significant effect on flow behaviour.

It is suggested that viscous heating could be used to improve surface finish and to reduce die swell of extrudates. However, considerably more experimental and theoretical work is required before the controlled use of viscous heating could be utilised as an aid in propellant processing.

8. ACKNOWLEDGEMENTS

The author would like to thank Dr F.S Baker and Mr R.E. Carter for many useful discussions.

NOTATION

C_p	heat capacity
Gz	Graetz number
h	heat transfer coefficient
k	thermal conductivity
L	die length
Nu	Nusselt number
P	pressure
r	radial coordinate
R	die radius
T	temperature
T_o	inlet temperature
$V_z(r)$	axial velocity
$V_r(r)$	radial velocity
w	mass flow rate
z	axial coordinate
γ	shear rate
η	viscosity
ρ	density
σ	shear stress

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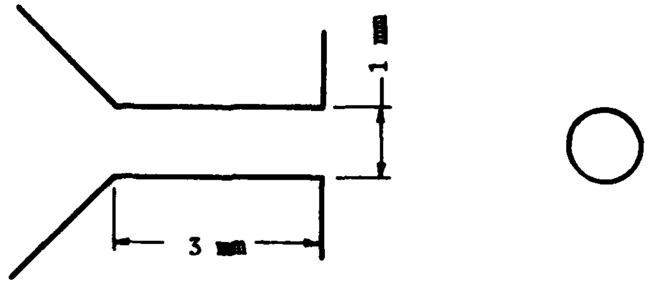
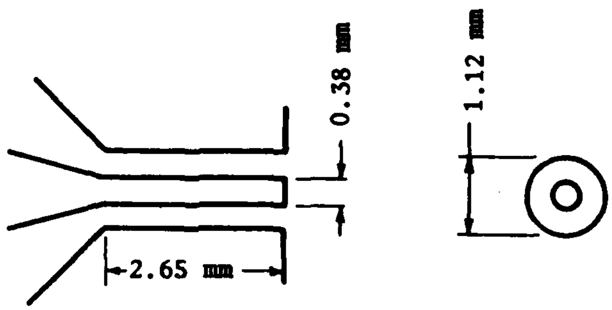
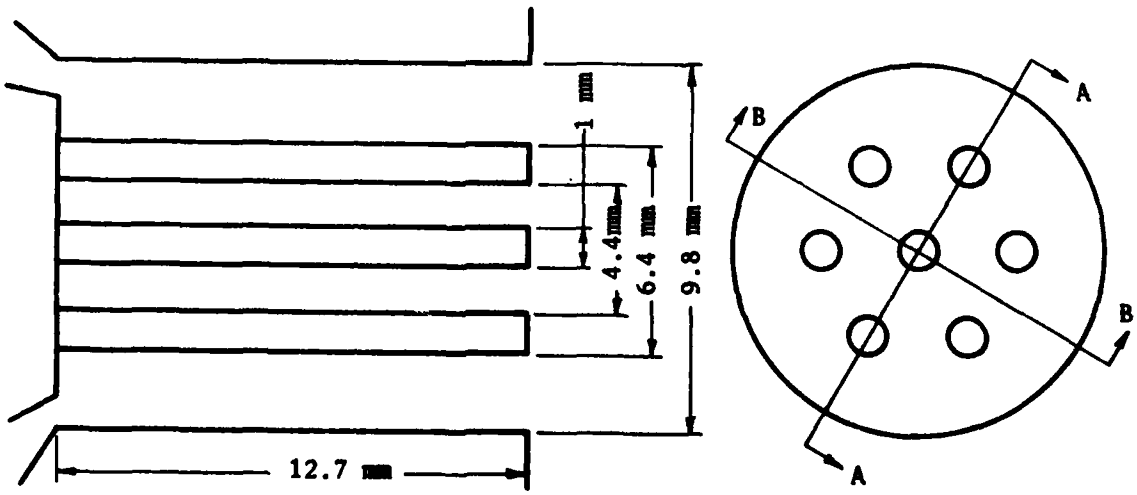


(a) Casting powder die



(b) Smallarms propellant die



(c) Cannon powder

Figure 1. Dimensions and geometries of dies

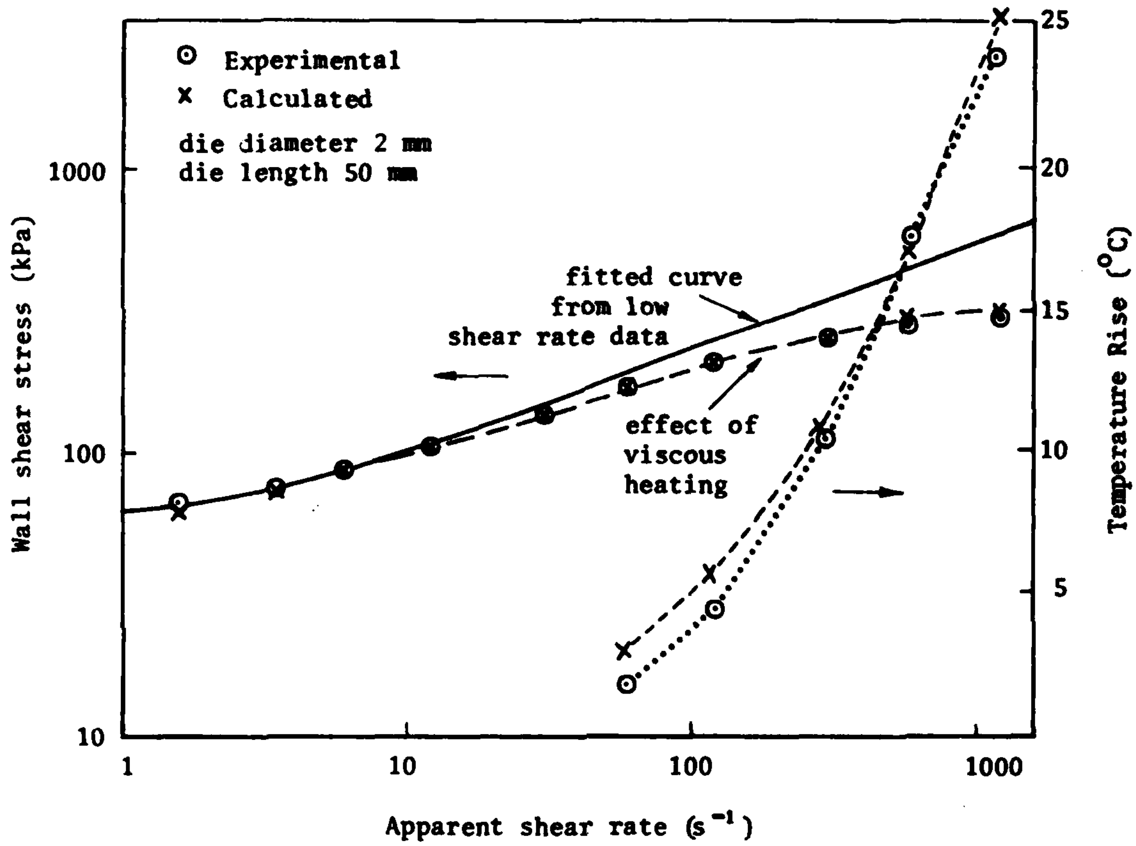


Figure 2. Shear stress as apparent shear rate(ref.4)

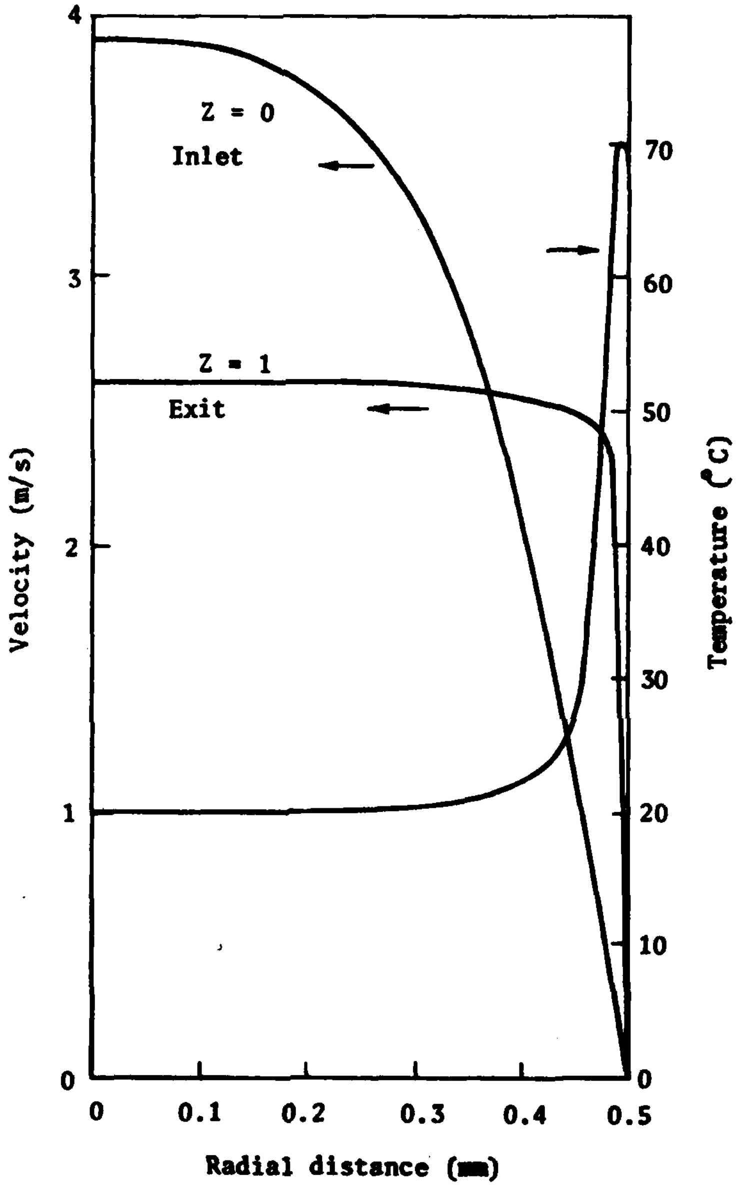


Figure 3. Velocity and temperature profiles for casting powder die

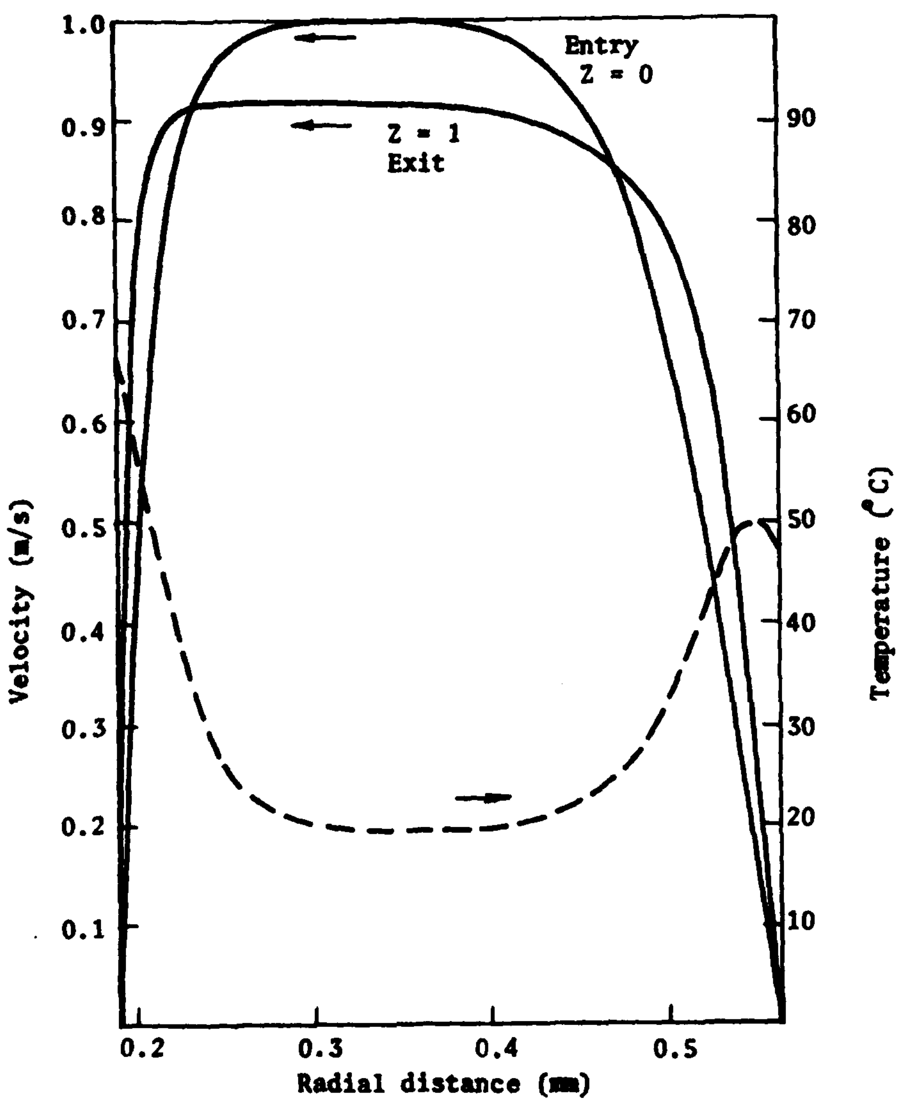


Figure 4. Velocity and temperature profiles for small arms propellant die

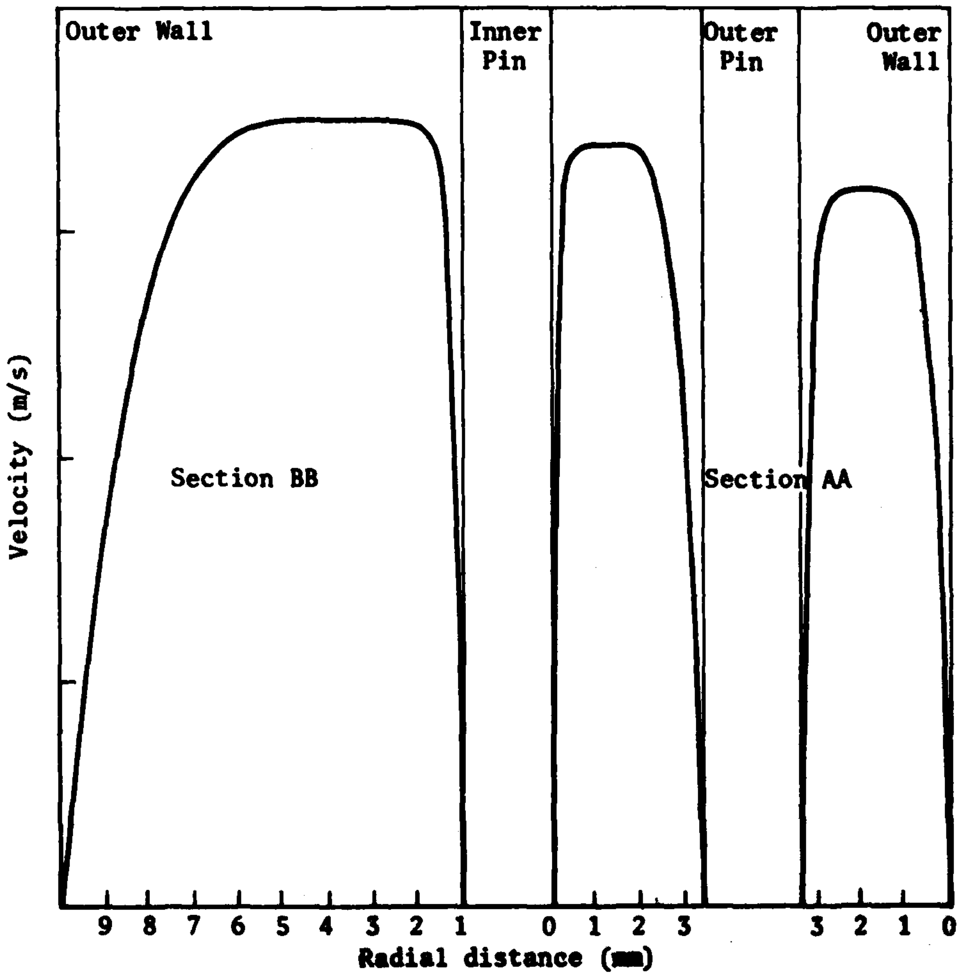


Figure 5. Velocity profiles in a cannon propellant die

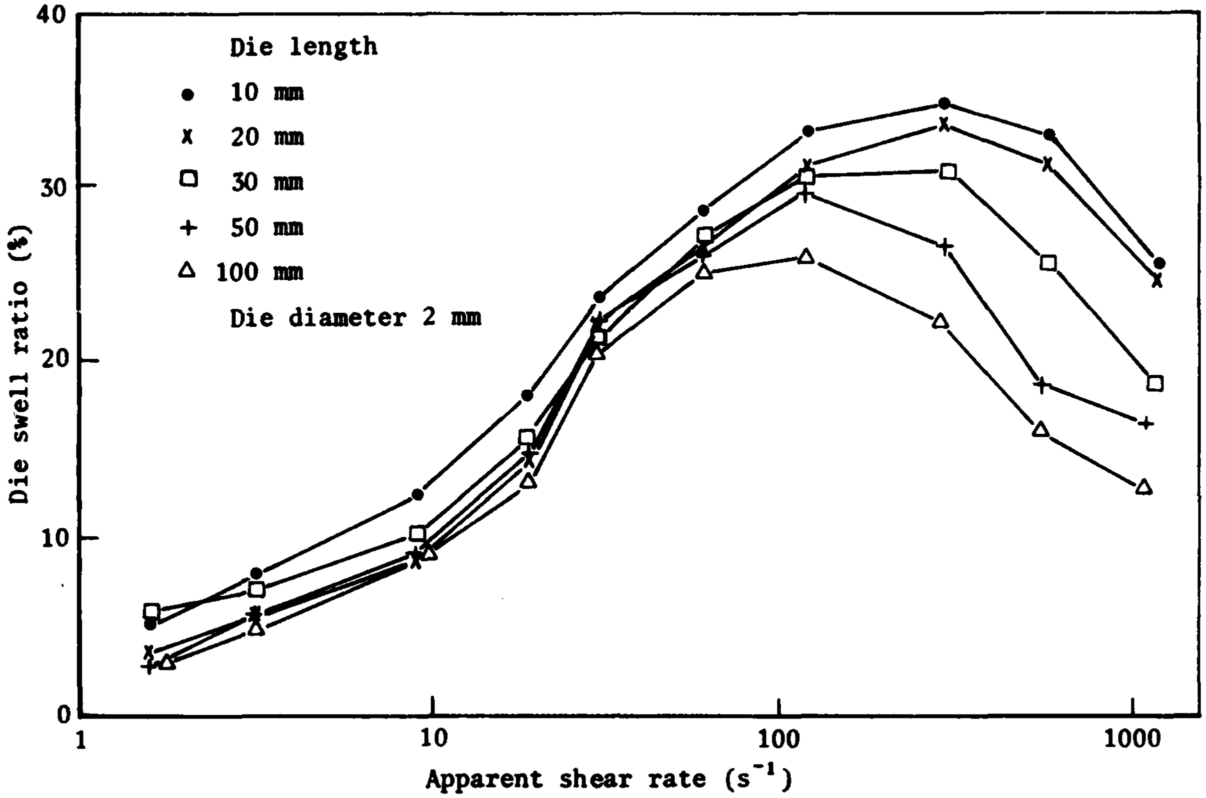


Figure 6. Die swell ratio (D-Do)/Do as apparent shear rate(ref.4)

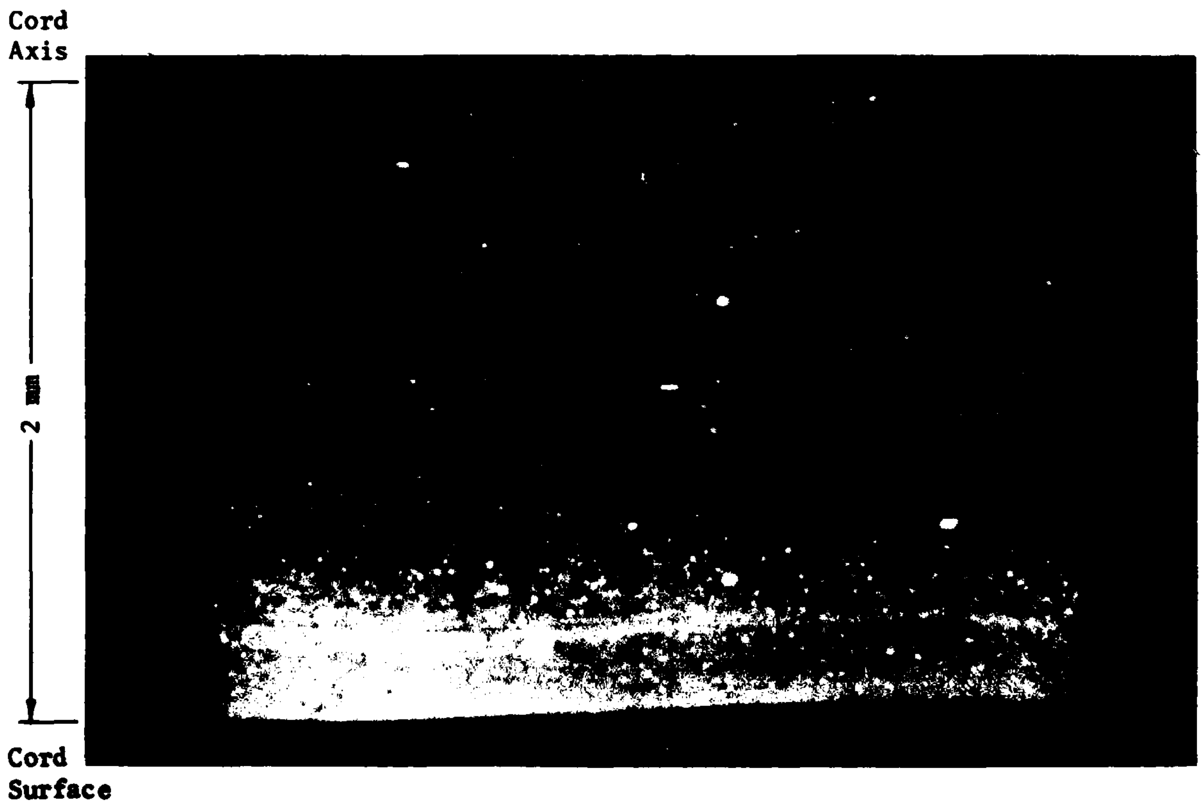


Figure 7. Micrograph of a section of propellant cord viewed through crossed polaroizers

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